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Author(s)	Luo, Yu; Deng, Dean; Xie, Lei et al.
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Prediction of Deformation for Large Welded Structures Based on Inherent Strain†

LUO Yu*, DENG Dean**, XIE Lei*** and MURAKAWA Hidekazu****

Abstract

Welding is one of the main joining techniques used in industry. Assembly in ships, cars, trains or civil engineering structures use this process more and more intensively. In this paper, the characteristics of the welding inherent deformation, namely longitudinal shrinkage, transverse shrinkage and angular distortion, of the Aluminum Alloy butt weld were investigated using the thermal elastic plastic finite element method. Through a series of FEM analyses, a database of inherent deformation was established. Based on the inherent deformation database, an elastic FEM was developed to predict the welding deformation for larger welded structures. The usefulness of the proposed method was demonstrated by the prediction of welding deformation for a large aluminum alloy coping.

KEY WORDS: (Elastic finite element) (Inherent strain) (Welding deformation) (Database)

1. Introduction

Welding induced deformation both degrades the performance and increases the cost of a fabricated structure. The finite element method is a very useful method to simulate welding distortion[1]. However, there are many difficulties when predicting a large welded structure such as a train coping. At present, the method to predict and control the welding distortion for a large welded structure mainly depends on experiences and not on theories or principles. If the welding distortion exceeds a tolerable limit, the weldment must be straightened to within fairness requirements after welding. Generally, it is very difficult to straighten welding deformation, especially for complex structures. Moreover, during the processing of the straightening, the additional stresses can be produced, and these stresses may promote brittle fracture, reduce the strength and decease the fatigue life. If the welding deformation of the large structure can be predicted beforehand, some measures can be adopted to reduce welding distortion. Therefore, it is important to predict the distortion for large welded structures.

When a thermal elastic plastic FEM is employed to predict the welding deformation, at first, the transient

Although this method can predict the deformation for small weldments, it is inapplicable for large weldments due to the large amount of time and computer capacity needed. In this study, the inherent strain method [2-4] has been applied to predict welding deformation of a large welded structure. The inherent strain namely Tendon Force, transverse shrinkage, and angular distortion, can be regarded as transitional variables to predict the deformation of the weldment. Using this method, it is unnecessary to track the entire welding process.

During heating and cooling in the welding thermal cycle, inherent strains occur in the weld metal and the base metal near the weld bead. The inherent strains are the source of the residual stress and deformation. When the weldment is at the state of neither external force nor internal stress, this state can be regarded as a standard state. The inherent strain ε* is the token of the strain shift comparing the free state with the standard state when a small element is taken away from the weldment, by which the stress is full released in the body. The value of the inherent strain can be expressed by the following equation.

$$\varepsilon^*=\varepsilon-\varepsilon_e \tag{1}$$

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*Associate Professor (Shanghai Jiaotong University, China)
** Foreign Research Fellow (Chongqing University, China)
*** Graduate Student (Shanghai Jiaotong University,China)
****Professor

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ε_e = elastic strain

The inherent strain includes plastic strain, thermal strain and the strain due to phase transformation during the thermal cycle. The thermal strain becomes zero after the weldment cools to room temperature. Finally, the inherent strain is composed of the plastic strain and the strain due to phase transformation.

During welding, the inherent strains generate in and around the weld joint. The residual stress and the deformation strongly depend on the magnitude and distribution of the inherent strain in the weld metal. Therefore, the inherent strain theory can be used to study and predict the welding distortion and the residual stress.

Generally, two methods can be used to obtain the inherent deformation due to welding. One is the experimental method, and the other is thermal elastic plastic finite element method.

In this paper, the thermal elastic plastic FEM was employed to built-up a database of the inherent deformation for aluminum alloy plate. Based on this database of the inherent deformation, through a simplifying welded structure, an elastic FEM with shell elements was developed to predict the welding distortion of a large welded structure namely a train coping.

2. Inherent Strain of Aluminum Alloy Plate

When the inherent strain is employed to predict welding distortion, the inherent deformation should be obtained beforehand. As mentioned above, there are two methods to obtain the inherent deformation. In this study, the thermal elastic plastic finite element method was used to establish a database of the inherent deformation for aluminum alloy plate. Three kinds of inherent deformation namely, longitudinal shrinkage (Tendon force), transverse shrinkage and angular distortion have been calculated.

The welding material is aluminum alloy, 5052, whose properties are shown in **Fig.1**.

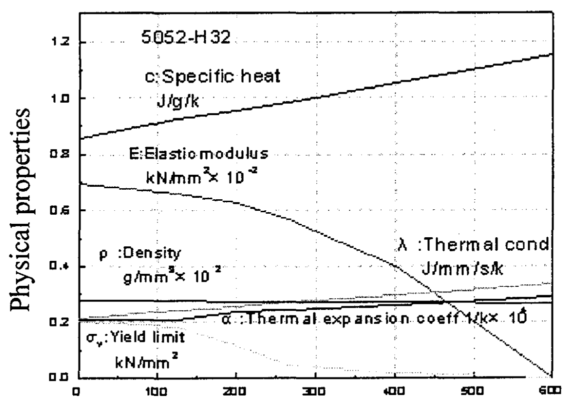

Fig.1 Thermo-physical and mechanical properties of aluminum alloy 5052.

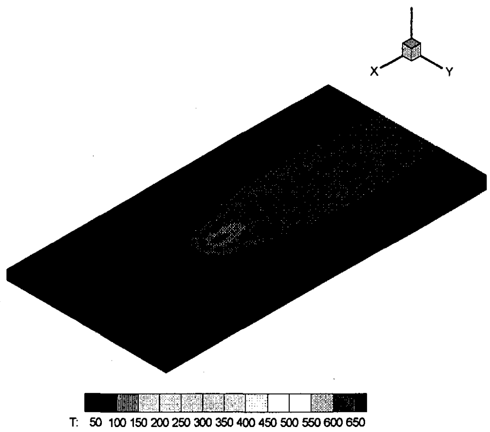

Fig.2 Finite element model and the transient temperature distribution during welding.

In order to establish the database of the inherent deformations for aluminum alloy plate, a 3-D model with 4000 elements and 5355 nodes was used as shown in Fig.2. It has a fine grid in the welding zone. The length, the width and the thickness of the model are 400mm, 200mm and 10mm, respectively. The transient temperature distribution during welding is also shown **Fig. 2**.

Generally, in practice, when welding parameters vary, the heat input also changes. In this study, a series of thermal elastic plastic FEM calculations with different heat input have been conducted, and the relationship between the inherent deformation and the heat inputs or the parameter (Q/h^2) has been obtained. Here, h is the thickness of the plate. The heat input Q is defined by the following equation.

$$Q=\eta IU/v \tag{2}$$

Where, I: the welding current

U: the welding voltage

v: the welding speed

η: arc efficiency

The relationship between Tendon Force and heat input Q is shown in **Fig. 3**. From this figure, it can be seen that the Tendon force is nearly proportional to the heat input Q. The relationship between transverse shrinkage and the parameter (Q/h^2) is shown in **Fig. 4**. It is clear that the transverse shrinkage is also proportional to the parameter (Q/h^2). In other words, when the parameter (Q/h^2) is larger, correspondingly, the Tendon force and transverse shrinkage also become larger.

The relationship between angular distortion and the parameter Q/h^2 is shown in **Fig.5**. From this figure, it can be observed that when the value of parameter Q/h^2 is less than 5.0J/mm^3, the angular distortion is roughly proportional to the parameter Q/h^2.

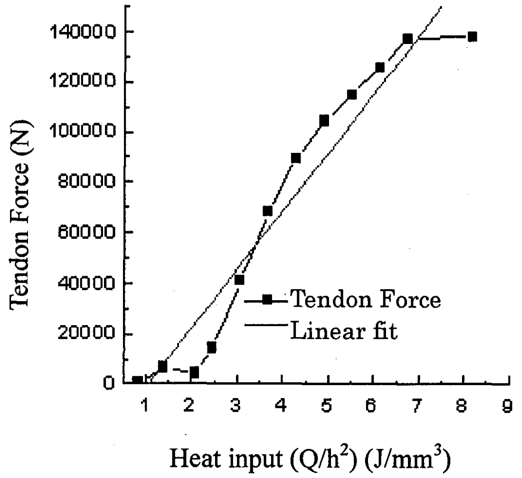

Fig.3 Relationship between Tendon Force and heat input.

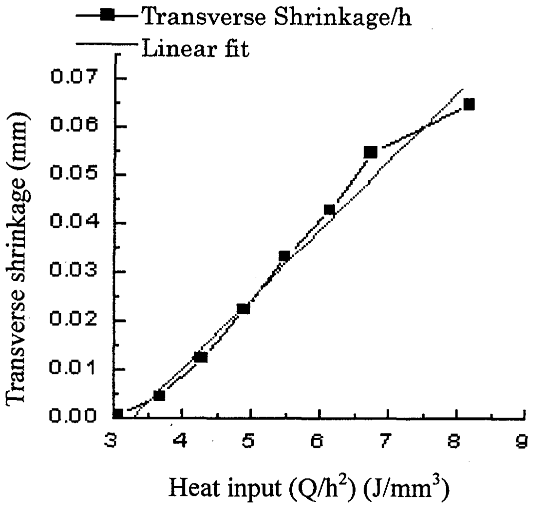

Fig.4 Relationship between traverse shrinkage and parameter Q/h^2.

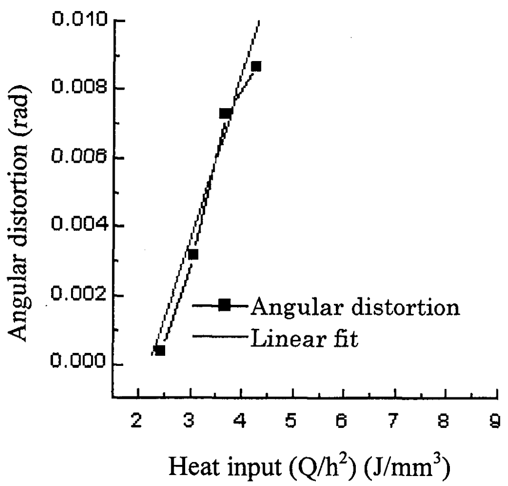

Fig. 5 Relationship between angular distortion and parameter Q/h^2.

When the welding parameters such as welding current I, arc voltage U, welding speed v and the thickness of plate h are known, the inherent deformations namely, Tendon Force, transverse shrinkage and angular distortion can be calculated from the database.

In the elastic finite element method proposed in this study, the inherent deformations can be changed into inherent strain when they are applied to predict welding deformation for welded structures.

3. Elastic FEM Simulation

3.1 Train Coping Structure

In this study, when using the inherent strain method to predict the welding deformation of the train coping, according to the characteristic of the welded structure the shell element is adopted. In this structure, the beam sub-structures should be simplified to shell sub-structures. In the present study, the principles of the equivalent Inertial Moment and equivalent Resisted-Bend Stiffness have been applied to simplify the structure.

In elementary beam theory, load is applied in a plane of symmetry of the member. Therefore load acts along a principal axis of the cross section, and lateral deflection is parallel to that axis. The small-deflection moment-curvature relation can be expressed as following:

$$\frac{d^2w}{dx^2}=\frac{M_y}{EI_y} \tag{3}$$

Where, w: the vertical direction deflection,
M: Moment
E: Young's Module
I_y : Moment of inertia

It is known that the bending distortion of a beam is related to the moment of inertia. If the moment of inertia is not changed, the bending stiffness will be a constant. Thus, for the sake of simple, in this model, the complex train coping has been transferred to the simply shell model according to the law of equal moments of inertia. For example, the following Moment of Inertia equation has been applied to simplify the structure as shown in **Fig. 6.**

$$\int_{-\frac{A}{2}+t}^{\frac{A}{2}-t} 2tydy + \int_{\frac{A}{2}-t}^{\frac{A}{2}} Bydy + \int_{-\frac{A}{2}}^{-\frac{A}{2}+t} Cydy = \int_{-\frac{A}{2}}^{\frac{A}{2}} Zydy \tag{4}$$

The train coping was simplified by applying the method mentioned above, and the simplified model is shown in **Fig. 7**.

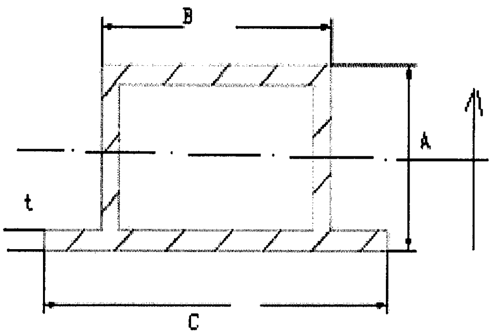

Fig. 6 Cross-section of a beam.

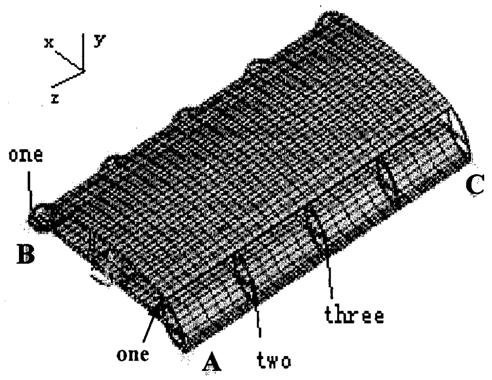

Fig.7 Simplified welded structure model along the train coping.

In this welded structure, the length is 5600mm, the width 2690mm, respectively. The number of elements in the shell model is 2518, and the nodes 2736. In this model, the number of the total welding lines is 62.

In this model, the heat input of each welding line was determined according to the welding conditions used in the experiment. The arc efficiency was assumed to be 0.6.

3.2 Inherent Strain

Special software that predicts the distortion of the weldment based on the inherent strain method was employed in the study. The software was developed by the Joining and Welding Research Institute in Osaka University and Shanghai Jiaotong University. In this software, only the location of the weld line, Tendon force, traverse shrinkage, and angular distortion or the heat input (Q) are needed for input, and the inherent deformation or the heat input can be automatically changed into inherent strain. Then, the welding deformation of a large weldment can be simulated.

3.3 Restrain Condition

The model is fixed at three points as shown in **Fig. 7** to prevent rigid body motion. Three displacement components in x, y, z directions at point A are fixed, and two displacement components in y, z directions at point B restricted. At point C, the vertical displacement component is also fixed.

3.4 Simulation Results

The longitudinal displacement distributions along the edge line -AC and the centerline are shown in **Fig. 8**, and the vertical displacement distributions along the edge line-AC and the centerline are shown in **Fig. 9**. Form Fig. 8, it can be seen that the longitudinal shrinkage of the centerline is approximately 4.5mm. On the other hand, the maximum deflections of both the centerline and the line-AC are close to 10.0mm.

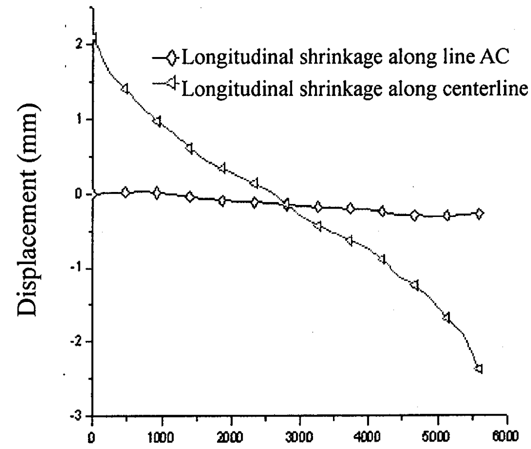

Fig.8 Longitudinal displacement of the AC line and the centerline.

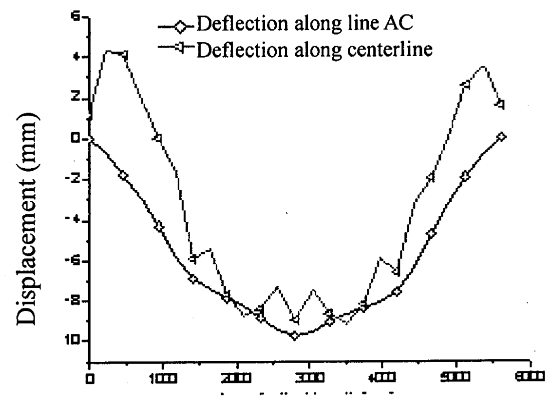

Fig. 9 Vertical displacement along the AC line and the centerline.

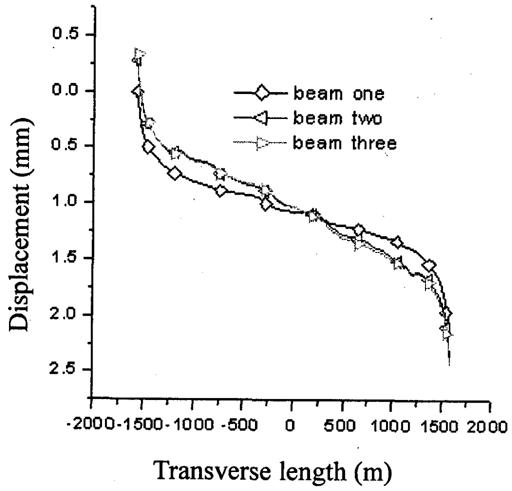

Fig. 10 Displacement of the three beams in the transverse direction.

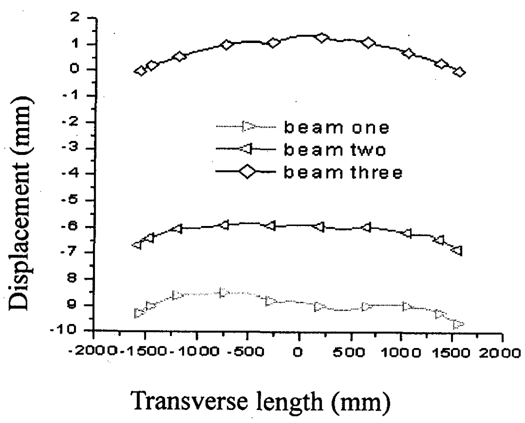

Fig. 11 Displacement of the three beams in the Y direction

The displacements of the three beams as shown in Fig. 7 in the transverse direction and the vertical direction are shown in the **Figs.10, 11**, respectively. From Fig. 10, we can see that for the transverse shrinkage of the beam one is 2.0mm, and those of the other two beams are almost the same. The values are slightly larger than that of the beam one. From Fig.11, it can be observed that the maximum deflection of the beam is only 1.0mm, and the deflection of the beam three is close to 10.0mm.

The final welding deformations of the large welded structure are shown in **Figs. 12,13,14.** Fig. 12 represents the transverse displacement, Fig.13 deflection, and Fig. 14 longitudinal displacement.

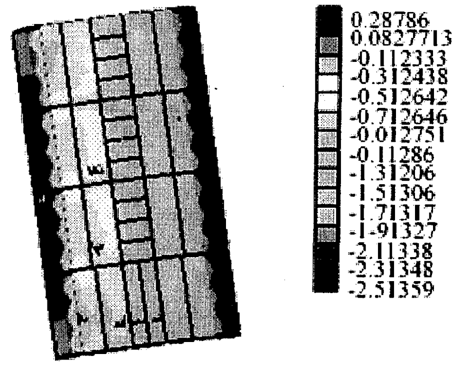

Fig.12 Displacement in the transverse direction.

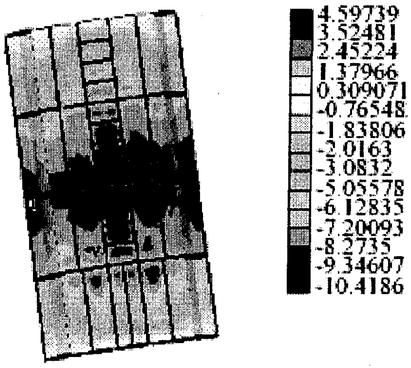

Fig.13 Displacement in the vertical direction.

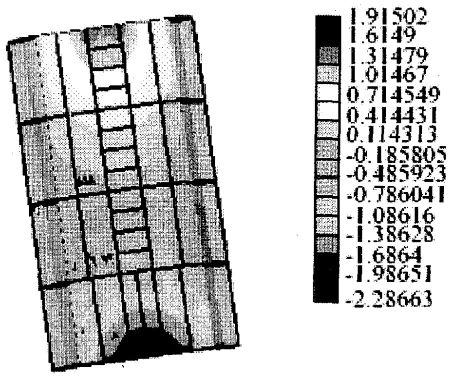

Fig.14 Displacement in the longitudinal direction.

4. Discussions

Through a series of thermal elastic plastic FEM analysis, the relationships between inherent deformation (Tendon force, transverse shrinkage and angular distortion) and the heat input or the parameter (Q/h^2) were established. According to practice welding parameters and the thickness of plate, using the obtained database of the inherent deformation, the inherent strain can be easily determined.

From the computed results, we can understand that it is unnecessary to divide the mesh very finely when the inherent strain method is employed. Therefore, using this method to predict welding deformation, even for large structure, takes a short computer time compared with the thermal elastic plastic FEM.

When the thermal elastic plastic finite element method is applied to predict welding deformation for large welded structures, the time increment should be not too large and the size of element should be small enough to obtain an acceptable result. Thus, a long computer time and a large memory are needed to complete the simulation. Therefore, it is impossible to calculate deformation for large welded structures using this method.

From the computed results, the final maximum of transverse shrinkage of beam three is approximately 2.8mm, and the corresponding experimental result is 3.0mm as shown in **Table 1**. In the same table, it can be seen that the longitudinal shrinkage of the centerline predicted by FEM is 4.5mm, and the experimental result is 6.0mm. The location of the maximum deflection is the center of the train coping, and the value is about 10.0mm. From the table 1, we can observe that the experimental result is 9.5mm, which is close to the simulation result. The longitudinal shrinkage has a symmetric distribution. The welding deformation is in good agreement with the experimental result. In other words, the inherent strain method is an effective method for predicting the welding distortion for large welded structures.

Table 1 Comparison with experiment

Deformation	Simulation results	Experimental result
Longitudinal shrinkage of the centerline	4.5mm	6.0mm
Transverse shrinkage of the beam three	2.8mm	3.0mm
Deflection of the centerline	10.0mm	9.5mm

5 Conclusions

To predict the distortion for large welded structures, a new finite element method was developed. In this method, thermal elastic plastic FEM was employed to establish relationships between the inherent deformation and the heat input or the parameter (Q/h^2). The shrinkage due to welding in large structures is taken into account by inherent strain. The efficiency of this method was demonstrated through simulating the welding deformation of a train coping structure. The conclusions that can be drawn from this investigation are the following:

1) The relationship between Tendon force (longitudinal shrinkage force), transverse method shrinkage, angular distortion and the heat input or the parameter (Q/h^2) have been obtained for the butt welded joint of the aluminum alloy.
2) It is unnecessary to track the whole welding process using the elastic shell finite element method based on the inherent strain. A very fine mesh is not needed to complete the calculation. Therefore, a lot of the calculation line will be saved. The characteristics of this method are distinct from other finite element methods.
3) The simulation results are in good agreement with experimental measurements. Even for large and complex welded structures such as train copings, the method proposed in this study can be used effectively to predict welding distortion.

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